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Finney,
Mark A.

FIRE-RELATED MORTALITY OF PONDEROSA PINE IN EASTERN MONTANA

Mark A. Finney

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Mark A. Finney
Systems for environmental Management
PO BOX 8868
Missoula MT 59807

Summary
Post-fire mortality data on ponderosa pine trees were analyzed from three sites in eastern Montana that were burned by wildfires in 1988. Data were analyzed for 1750 trees. The analysis suggested that after four years, both the largest and smallest trees had the highest probability of dying. This contrasts with models for most other species that reflect lower mortality rates for larger trees that have greater resistance to injury. As expected, predictions made using injury variables (crown kill, and girdling) performed better than predictions made using only damage variables (crown scorch, bark char).

Introduction

The purpose of this research was to analyze ponderosa pine mortality data collected from eastern Montana between 1988 and 1992 for comparison with mortality responses of other tree species in the northern Rockies. Mortality has been studied for many other species from the western U.S. (Ryan and Reinhardt 1988, Ryan et al. 1988, Peterson and Arbaugh 1986) leading to practical models for predicting survival of trees damaged by fire. The work to date on ponderosa pine has produced several descriptive models of mortality after wildfires in California (Regelbrugge and Conard 1993) and prescribed fires in Idaho (Saveland et al. 1990), Colorado (Wyant et al. 1986), and Arizona (Harrington 1993). Other work on ponderosa pine has examined growth responses after prescribed burning (Landsberg et al. 1984, Peterson et al. 1994). So far, no widely applicable models of ponderosa pine mortality have been developed for the northern Rocky Mountains.

Methods

The data were provided from three sites in eastern Montana burned by wildfires in 1988 (Earlybird, Air Patrol, and Brewer). Damage variables used for analysis were recorded for each tree, observed within weeks after the fires (percentage crown volume scorched, lower and upper bark char height). Actual injuries to the tree (percentage crown volume killed, percentage girdling) were assessed in spring of 1989. Annual observations on tree status were included in the data through 1992 at which time the cumulative mortality was assumed to be final with respect to fire injuries (subsequent mortality would be difficult to distinguish from background levels or causes independent of the fire). Bark beetle activity on each tree was assessed visually each year based on external evidence of boring dust and pitch tubes and classified into one of four categories. These categories were intended to be used for exploratory analysis only.

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Logistic regression was used to relate final tree mortality (as of 1992) to various sets of independent variables. The analysis had three primary goals:

1. to evaluate the performance of previous model forms of tree mortality (specifically Model 1 from Ryan and Reinhardt (1988) and the model of Ryan and Amman (1994),
2. to compare mortality models that used damage variables (crown scorch, bark char height) versus injury variables (crown kill, girdling), and,
3. to find the model that had explained the most variation in the data.

To accomplish objective #1, several forms of the logistic equation were applied to the ponderosa pine data that were developed for seven other tree species. The model of Ryan and Reinhardt (1988) is based on bark thickness (BT) as calculated from diameter, and percentage of crown kill (CK):

$$P = 1/1 + e(b_0 + b_1 BT + b_2 BT^2 + b_3 CK^2)$$

and by Ryan and Amman (1994):

$$P = 1/1 + e(b_0 + b_1 (1 - e^{-BT}) + b_3 CK^2)$$

In the attempt to explain the most variation in the data, regressions were performed using dummy variables for site location. These were tested in the logistic regression for both intercept and interaction with the other variables.

Model performance was assessed using the log-likelihood statistic and the receiver operating characteristic (ROC) curves for each model (Saveland and Neuenschwander 1990). Also models were plotted to visualize the variation in mortality as a function of the independent variables.

Results

A total of 1750 trees were included in the analysis; several were removed before analysis because they were uprooted or broken before observations ceased in 1992. 664 of the trees had died by 1992. Trees varied between 5 inches DBH and 24 inches. Mortality increased substantially between the first and fourth year (Table 1). The proportion of trees having the highest observed insect activity increased slightly from 1988 to 1992 (Tables 2 and 3).

Most trees were between 8 and 16 inches (20 and 40 cm) in diameter (Figure 1). Figure 1 also suggests that the percentage of mortality was U-shaped with respect to diameter, indicating that trees in middle size classes had lower mortality rates than either the larger or smaller trees. Both Early Bird and Air Patrol showed similar mortality trends, although Brewer did not (Figure 2 through Figure 4).

Regression analysis for the combined data sets using the equation form developed by Ryan and Reinhardt (1988) (based on bark thickness and crown kill) reflected the U-shaped trend (Figure 2, Table 4). However, when girdling was included, only diameter-squared (or bark thickness-squared) was significant (P=0.05), (Table 4). Girdling also changed the shape of the regression

model with respect to diameter variation, suggesting higher mortality rates for large trees for equivalent injury. The bark thickness variable used by the model form of Amman and Ryan (1994) was not significant, probably because its negative exponential form decreases the influence of bark thickness with increasing diameter. This is substantially different from the power-curve shape produced by squaring bark thickness (or diameter) found in the equation form from Ryan and Reinhardt (1988).

All damage and injury variables showed positive associations with mortality. Injury variables (crown kill, girdling), however, were stronger predictors of mortality than damage variables (crown scorch, bark char height), as reflected by the lower log-likelihood statistics (Table 4) and greater area under the ROC curves (Figure 5).

The ROC curves gave the same relative results as the log-likelihood regression statistics in terms of comparing model performance (Figure 5). When the ROC analysis was performed for different diameter classes, the models also suggested that the responses of smaller trees are more reliably predicted than larger trees (Figure 6).

Not surprisingly, the best model found for explaining the data included tree size and injury variables (Table 4). It also suggested significant influence of site on the DBH^2 term (Earlybird vs. Brewer and Air Patrol) and girdling (Brewer vs. Earlybird and Air Patrol). Dummy variables used for the intercept and crown kill were not significant (Appendix 1).

Discussion

The regression analysis for all models consistently suggested that probability of mortality increased with larger diameter ponderosa pine trees. This contrasts with models of mortality for most other species, in which larger trees are more resistant to fire injuries and other models of ponderosa pine trees (Regelbrugge and Conard 1993, Wyant et al. 1986, Harrington 1993). Several hypotheses may help explain this trend. First, larger trees may have suffered more fire damage because of higher fuel loadings around them. Greater productivity of larger trees means more deposition of litter fuels near their base, leading to potentially longer duration heating of basal tissues (Ryan and Frandsen 1992). For given fire behavior and fuel conditions, larger trees often receive less damage to stems and foliage because of thicker bark and taller crowns, respectively. Second, larger trees may have a physiological disadvantage in recovering from a given level of injury. Greater respiratory demand from larger plant organs (stem, foliage, roots) may diminish the energy available to both repel insect attack and to recover from injuries to those organs. Most data sets on tree mortality have greater damage or injury on smaller, making direct comparisons between similar damage levels across tree sizes difficult. Third, larger trees may be more suitable or desirable hosts for phloem feeding beetles. Thicker phloem of larger trees is better suited to survival of beetle broods than the thinner phloem of small trees. Perhaps a combination of these three factors may jointly contribute to the observed mortality of larger trees.

The uneven contribution of insect damage to mortality of larger trees was revealed by the consistently higher proportion of the highest insect activity in the smallest and largest diameter classes in each year (1989, 1990, 1992) (Table 5a-c). However, because insect activity can both

follow and precede death, it is impossible from these data to determine causation. Logically, however, smaller trees with thin phloem and bark should display higher insect activity after death (probably from wood borers and Ips spp.), whereas larger trees with thicker phloem and bark would be attractive to insects before death (probably phloem feeders like Dendroctonous spp). Small trees may be less suitable hosts to bark beetles because of their thin phloem; thin bark of smaller trees also provides less protection from heat injury to this thin phloem during fires. The thick bark of large trees generally protects the thicker phloem from heating but is also better suited to successful hosting of broods of bark beetles (Dendroctonous spp).

Although crown scorch immediately following the fire was a significant predictor of mortality it did not explain as much variation as crown kill. Ponderosa pine is well known to be capable of recovering from defoliation if the buds remain alive (Wagener 1961, Dieterich 1979). Crown kill was typically lower than the recorded value of crown scorch, showing a correlation for all data combined of r=0.86. Differences in the correlation between crown scorch percentage and crown kill percentage were found by site however, with Earlybird r=0.944, Airpatrol r=0.872, and Brewer r=0.816. For salvage appraisal, it is often impractical (because of wood deterioration) to wait until crown kill is distinguishable before making harvest decisions. Thus, crown scorch is a useful model for those applications. The regression model that contains girdling as a predictor variable will be less useful for practical application because of the difficulty in measuring girdling directly. However, it may be possible in the future to predict girdling for use in prescribed burning based on fuel consumption.

The best model for explaining the ponderosa pine data based on injury variables contained significant site effects for DBH^2 (between Brewer and Earlybird) and girdling (between Brewer and Airpatrol), but not CK^2 or the equation intercept. A squared term for DBH and CK always performed better than just DBH or CK and reflects the increasing seriousness of those injuries to mortality as their values increase (Ryan and Reinhardt 1988). By contrast, a similar model using only damage variables showed significant site effects for the intercept (between Brewer and Airpatrol), DBH^2 (between Brewer and Earlybird), CS^2 (between all sites), and LBC (between Earlybird and Airpatrol). Clearly, differences between sites were not consistent for the damage or injury variables, suggesting that the significance of site was caused by the peculiarities of the data sets on individual sites (like fuel loading, fire behavior, insect attacks, range of diameter etc). However, it was interesting that the influence of crown scorch on mortality was significantly different among all sites whereas crown kill influence was not. The differences in correlation coefficients between sites supports the idea that the timing of the fires relative to the phenology of foliar growth and bud formation had some effect on mortality. Although ponderosa pine is known to recover well from crown scorching (Wagener 1961, Dieterich 1979), this response relies on survival of the buds. If buds have not been formed before the fires, a greater degree of mortality might be expected for a given level of crown scorch, as seen in the correlation between crown scorch and crown kill for Earlybird with r=0.944 which likely occurred before buds had formed completely. The other fires, Air Patrol and Brewer (r=0.872 and r=0.816, respectively) occurred after bud formation, which could contribute to the lower correlation coefficients. This might explain the absence of significant differences in the effects of crown kill on mortality of the different sites, because the actual amount of crown death would eliminate variation caused by different responses to crown scorch. These results, however, must be viewed with some caution because the scatter plots of crown kill vs. crown scorch reveal

tremendous variation. Some trees even had greater percentage crown kill than percentage crown scorch. This might be possible where insects exacerbated the crown damage.

Conclusion

The main findings of this study were that the equation form developed by Ryan and Reinhardt (1988) was acceptable for predicting ponderosa pine mortality, but that it suggested higher rates of mortality for the largest trees in the sample. Also, injury variables were better predictors of mortality than damage variables, probably because of the additional variation in how trees recover from a given level of damage. However, damage variables are easy to measure and can be used to predict mortality in advance of detecting actual injury to the tree (i.e. for salvage uses). The contribution of insects to mortality of the larger trees is suggested by these data as well, but is inconclusive as to the mechanism of insect involvement (either causing or following tree death). The data seem to suggest a small increase in crown injury resulting from a given level of crown scorch, perhaps because one fire occurred before complete bud formation or perhaps because of insect damage.

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Table 1. Frequency/Total and Percentage of dead trees as of 1989-1992.

	Girdling (%)			
Crown Scorch (%)	**0-25%**	**26%-50%**	**51%-75%**	**76%-100%**
0-25%	4-49/478 (1-10%)	3-22/48 (6-46%)	0-5/16 (0-31%)	1-9/9 (11-100%)
26-50%	6-47/244 (2-19%)	2-20/52 (4-38%)	0-9/22 (0-41%)	5-10/12 (42-83%)
51-75%	6-57/226 (3-25%)	4-35/59 (7-59%)	1-16/25 (4-64%)	9-25/25 (36-100%)
76-100%	95-163/287 (33-56%)	53-101/120 (44-84%)	11-33/50 (22-66%)	51-76/77 (66-99%)

Table 2a. Frequency and Percentage of Insect Activity (4 categories) in 1989 by damage class.

	Girdling (%)			
Crown Scorch (%)	**0-25%**	**26%-50%**	**51%-75%**	**76%-100%**
0-25%	355+58+46+19= **478** 74,12,10,4%	26+4+9+9= **48** 54,8,19,19%	12+3+1+0= **16** 75,19,62,0%	2+3+1+3= **9** 22,33,11,33%
26%-50%	147+35+26+26= **234** 60,14,15,11%	22+3+19+8= **52** 42,6,37,15%	13+0+6+3= **22** 59,0,27,14%	5+0+1+6= **12** 42,0,8,50%
51%-75%	143+24+31+28= **226** 63,11,14,12%	20+6+18+15= **59** 34,10,31,25%	13+0+4+8= **25** 52,0,16,32%	7+0+4+14= **25** 28,0,16,56%
76%-100%	134+26+31+96= **287** 47,9,11,33%	20+12+8+70= **120** 17,10,15,58%	23+5+6+16= **50** 46,10,12,32%	16+2+8+51= **77** 21,3,10,66%

Table 2b. Frequency and Percentage of Insect Activity (4 categories) in 1992 by damage class.

	Girdling (%)			
Crown Scorch (%)	**0-25%**	**26%-50%**	**51%-75%**	**76%-100%**
0-25%	258+127+57+36= **478** 54,27,12,8%	5+18+15+10= **48** 10,38,31,21%	3+4+5+4= **16** 19,25,31,25%	1+3+2+3= **9** 11,33,22,33%
26%-50%	98+71+44+31= **244** 40,29,18,13%	9+12+23+8= **52** 17,23,44,15%	5+4+9+4= **22** 23,18,41,18%	0+3+1+8= **12** 0,25,8,67%
51%-75%	94+61+36+35= **226** 42,27,16,15%	1+15+21+22= **59** 2,25,36,37%	3+7+6+9= **25** 12,28,24,36%	2+1+5+17= **25** 8,4,20,68%
76%-100%	83+56+40+108= **287** 29,20,14,38%	6+11+28+75= **120** 5,9,23,63%	2+13+12+23= **113** 4,26,24,46%	3+3+15+56= **77** 4,4,19,73%

Table 3. Observed frequencies of insect activity on ponderosa pine trees by diameter class for (a) 1989, (b) 1990, and (c) 1992. Expected frequencies in parentheses from Chi-square analysis.

1989

Insect Activity	Diameter 5-10 inches	Diameter 10-15 inches	Diameter 15-20 inches	Diameter 20-25 inches	**Total**
0	387/423	463/407	100/113	8/15	**958**
1	59/80	89/77	28/21	5/3	**181**
2	98/106	97/102	39/28	5/4	**239**
3	229/164	95/158	39/44	9/6	**372**
Total	**773**	**744**	**206**	**27**	**1750**

1990

Insect Activity	Diameter 5-10 inches	Diameter 10-15 inches	Diameter 15-20 inches	Diameter 20-25 inches	**Total**
0	314/352	391/339	88/94	5/12	**798**
1	82/111	127/107	37/29	5/4	**251**
2	125/123	110/118	37/33	6/4	**278**
3	252/187	116/180	44/50	11/7	**423**
Total	**773**	**744**	**206**	**27**	**1750**

1992

Insect Activity	Diameter 5-10 inches	Diameter 10-15 inches	Diameter 15-20 inches	Diameter 20-25 inches	**Total**
0	226/253	279/244	64/67	4/9	**573**
1	141/181	208/174	55/48	5/6	**409**
2	145/141	128135	40/38	6/5	**319**
3	261/198	129/190	47/53	12/7	**449**
Total	**773**	**744**	**206**	**27**	**1750**

Table 4. Final equations predicting ponderosa pine mortality.

Equation[1]	Log Likelihood	ROC
$P = 1/(1 + e(6.411BT - 4.891BT^2 - 5.799CKf^2))$	-790.275	0.823
$P = 1/(1 + e(3.407 - 0.004DBH^2 - 5.774CKf^2 - 4.4GF))$	-667.297	0.879
$P = 1/(1 + e(0.354DBH - 0.014DBH^2 - 2.415CSf^2 - 0.151LBC))$	-893.695	0.798

1 *DBH* =diameter at breast height (in)
BT =bark thickness (in) =-3=0.376+0.0584 DBH (Ryan 1982).
CKf =crown kill fraction (0-1)
Gf =girdling fraction (0-1)
LBC =lower bark char height (ft)
CSf =crown scorch fraction (0-1)

Figure 1. Frequency of tree survival and mortality for all sites combined

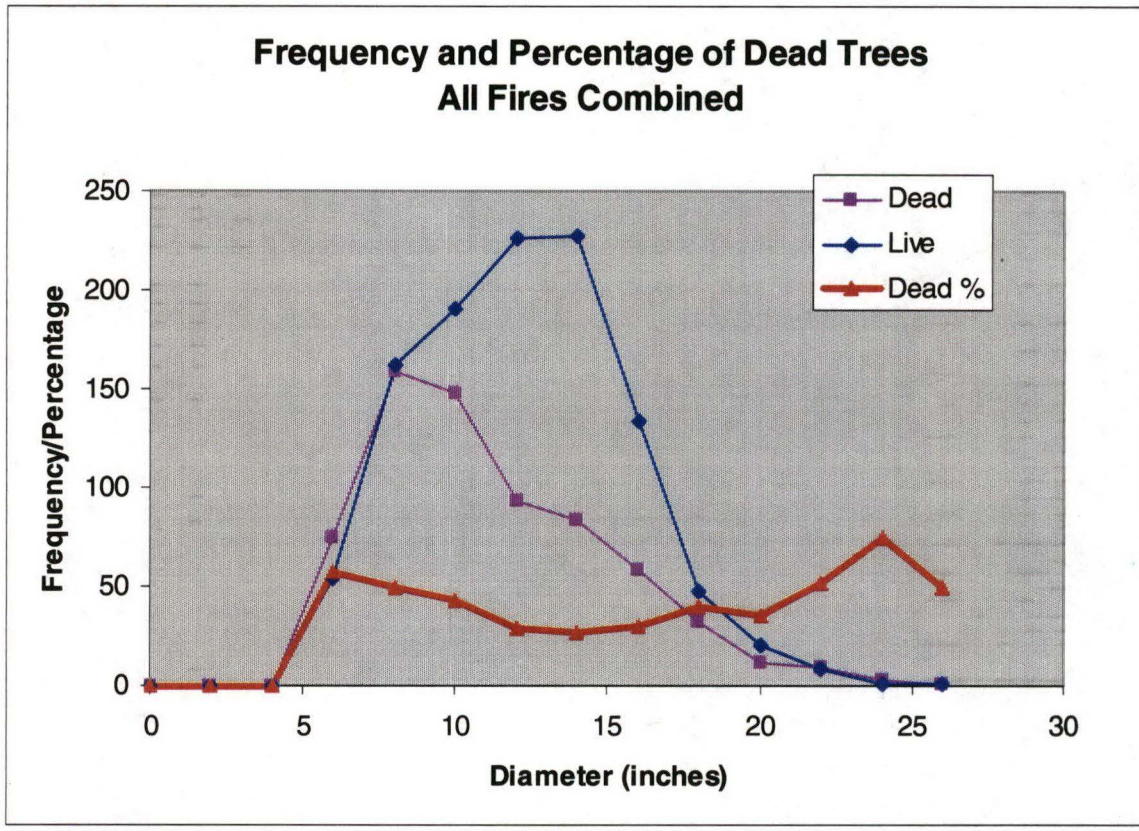
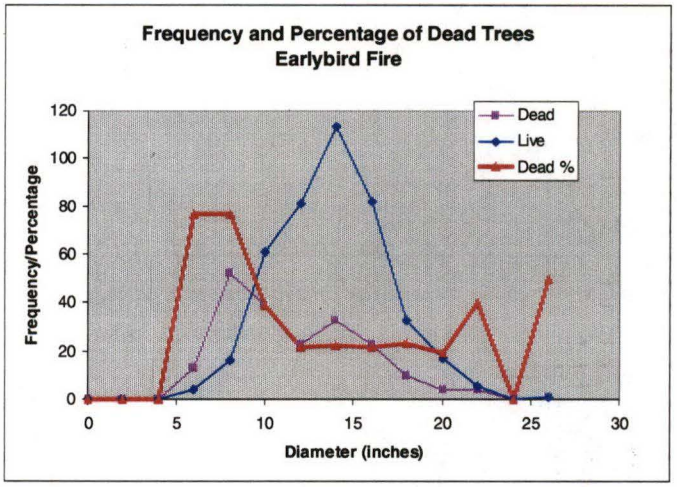
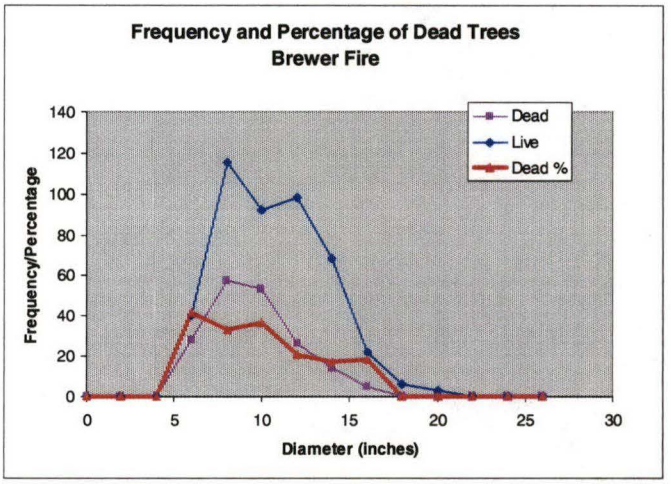


Figure 2. Frequency of tree survival and mortality for individual sites.





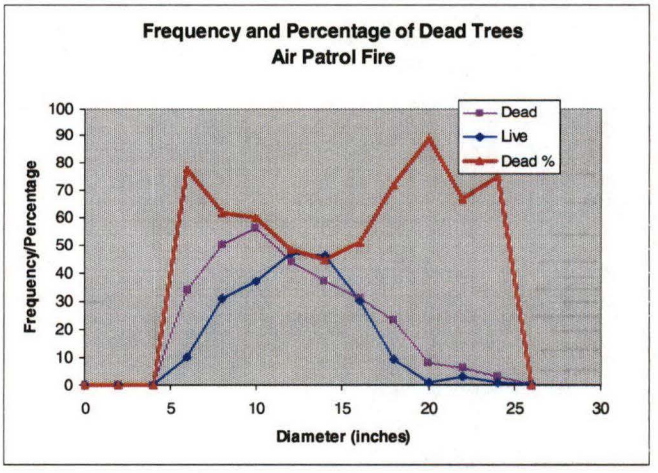


Figure 3. Comparison of ponderosa pine mortality model with the Ryan and Reinhardt (1988) model for other tree species.

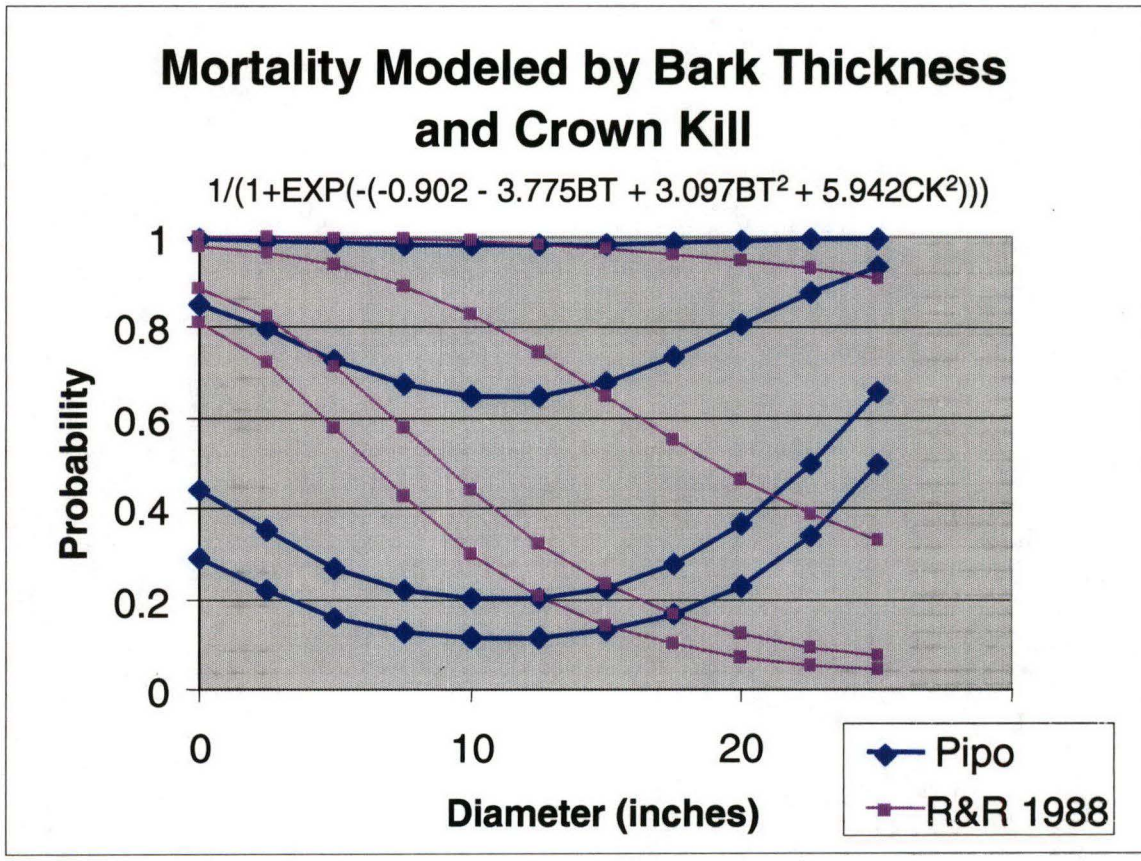


Figure 4. Ponderosa pine mortality modeled from injury variables.

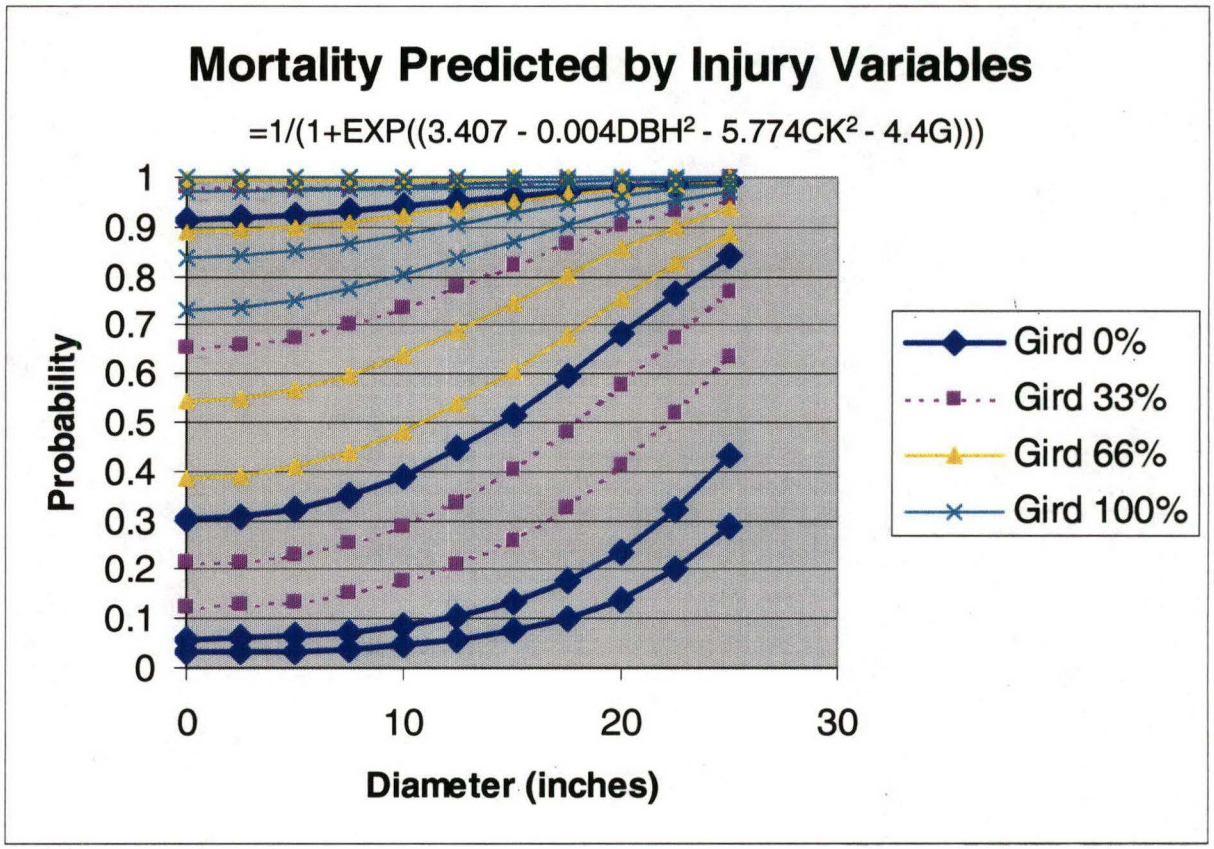


Figure 5. Comparison of ROC curves for different models (see Table 4 for modelform). ROC values represent the fractional area beneath each curve.

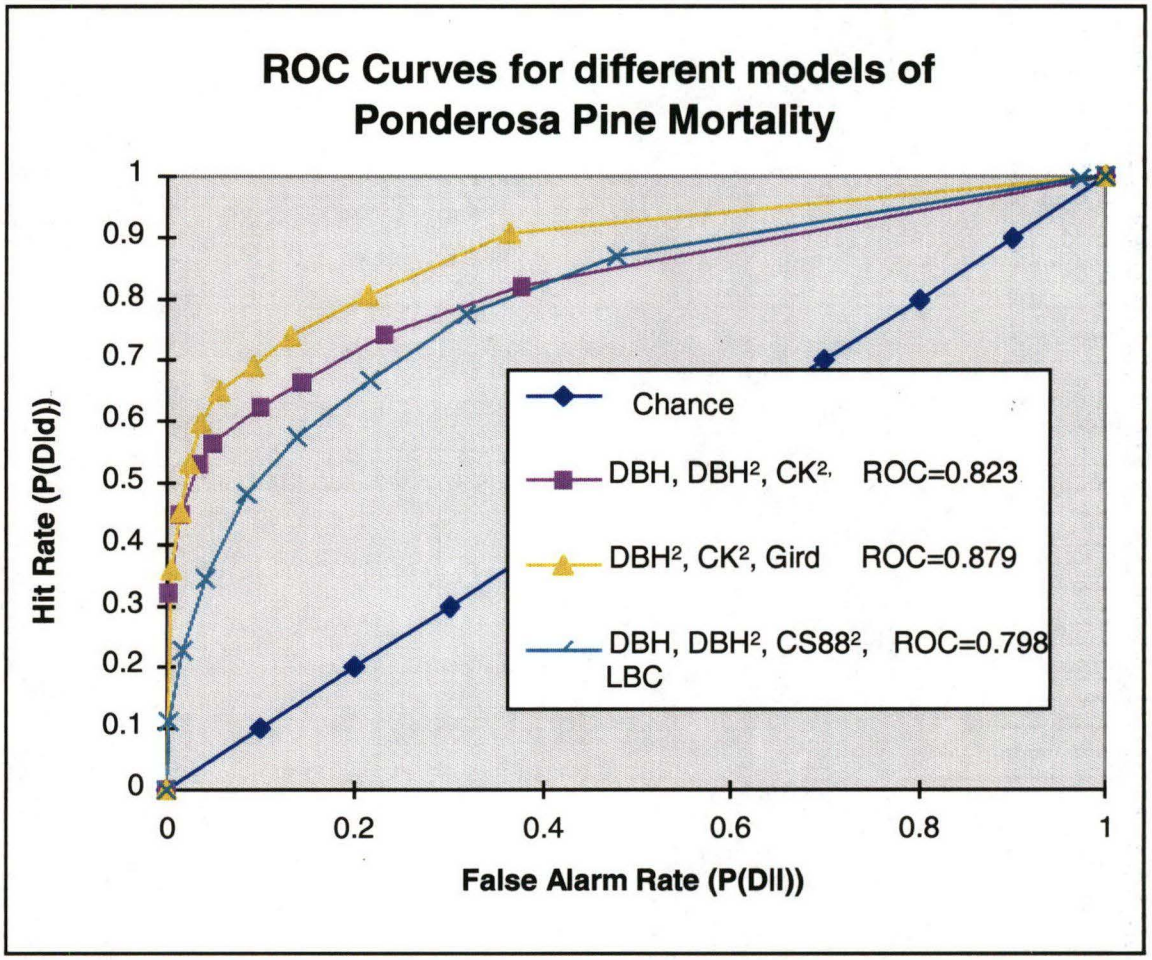
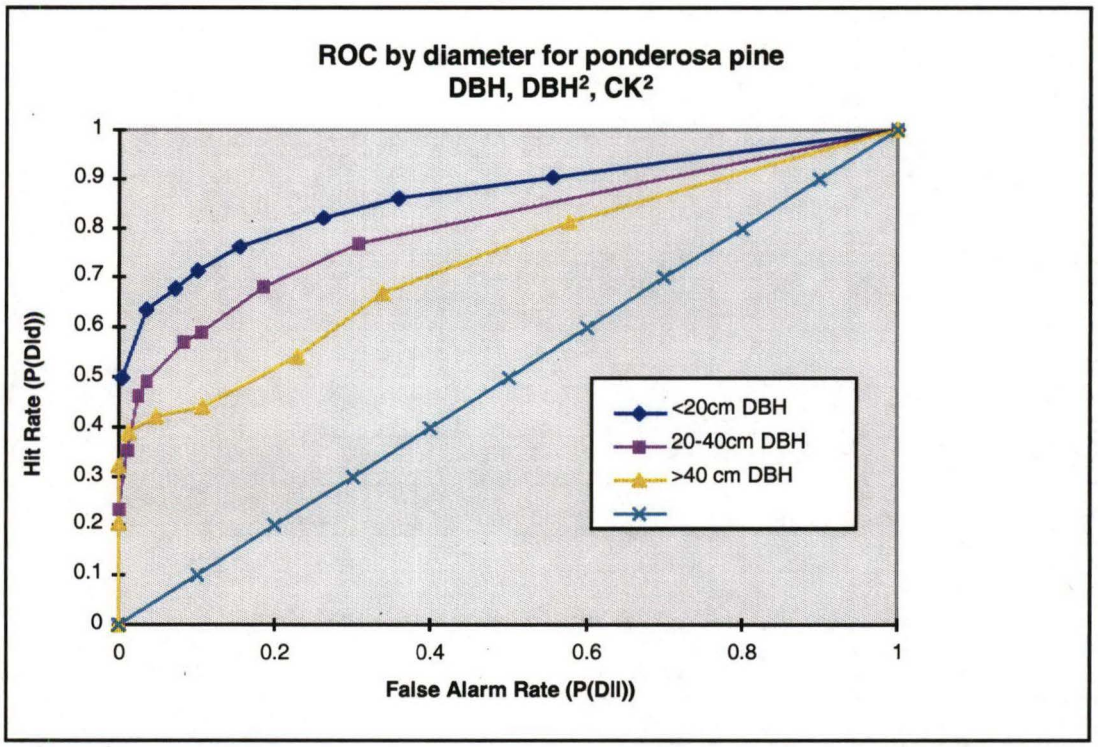


Figure 6. ROC curves by diameter class for two models using injury variables. (see Table 4 for model form and statistics).



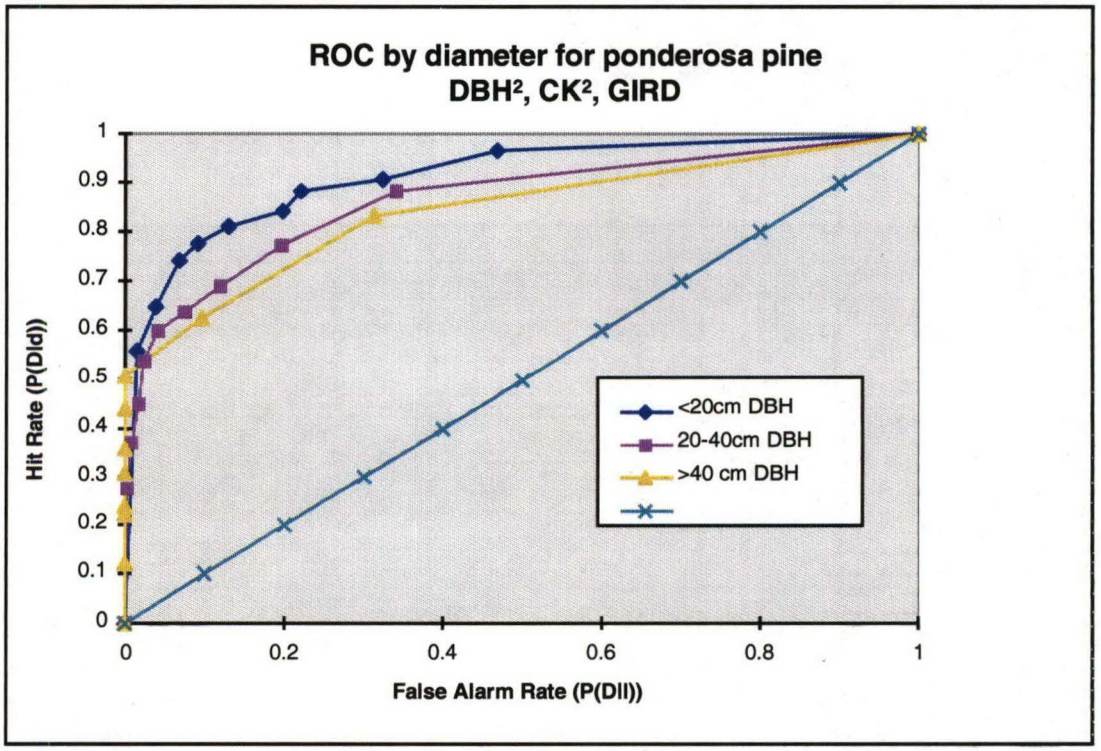


Figure 7. Scatterplots of crown kill vs. Crown Scorch for each site.